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AN "IN-STACK" DIFFUSION CLASSIFIER FOR AEROSOL MASS DISTRIBUTION MEASUREMENT

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A five-stage, screen-type diffusion classifier was designed and built to make in-situ measurement of submicron aerosols at temperatures and pressures encountered in industrial-type exhaust stacks. Laboratory calibration proceeded satisfactorily and held strong promise of successful field demonstration. However, major problems were encountered in test procedures during both field tests (at the Jacksonville Florida Electric Authority (J.E.A.) Southside generating Station, Unit #4 (oil-fired boiler) and the Naval Air

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Rework Facility, Jacksonville, Jet Engine Test Cell #11 (J-52 engines). Conditioning of the glass fiber filters to sulfur oxides was not done at the Southside Power Plant - this appears to have been the major problem there. Temperatures of the exhaust stack exceeded 200° C at the Jet Engine Test Cell - consequent weight loss due to grease vaporization appears to have been the problem there.

Preface

This study was jointly funded by the HQ AFESC Engineering and Services Laboratory (ESL) and the Environmental Protection Agency's Environmental Sciences Research Laboratory (EPA/ESRL), Research Triangle Park, NC 27711. This work was conducted under EPA grant # R805762-010. The EPA project officer was Dr. Kenneth T. Knapp. Major Joseph A. Martone was the initial project officer at the HQ AFESC. The study was performed by Dr. Dale A. Lundgren and Cumbum N. Rangaraj of the Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This final technical report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION	1
II	CONCLUSIONS	3
III	APPARATUS AND EXPERIMENTAL PROCEDURES	5
	1. DIFFUSION CLASSIFIER DESCRIPTION	5
	2. AEROSOL GENERATION	6
	a. Test Aerosols	6
	b. Collison Atomizer	6
	c. TSI Model 3071 Electrostatic Classifier	7
	3. PENETRATION MEASUREMENT	8
	a. TSI Model 3030 Electrical Aerosol Analyzer	8
	b. TSI Model 3068 Aerosol Electrometer	8
	4. TEMPERATURE AND FLOW RATE MEASUREMENT	9
	5. EXPERIMENTAL SETUP	9
	6. EXPERIMENTAL PROCEDURE	11
	7. SPECIAL CONSIDERATIONS	13
IV	FIELD TESTING	15
	1. TEST PROCEDURE	15
	2. SPECIAL CONSIDERATIONS	16
V	RESULTS AND DISCUSSION	17
	1. LABORATORY TESTS	17
	a. Development of Semi-Empirical Penetration Function	17
	b. Effect of Particle Size on Penetration	17
	c. Effect of Temperature on Penetration	19
	d. Effect of Flow Rate on Penetration	19
	e. Effect of Number of Screens on Penetration	22
	f. Effect of Aerosol Type on Penetration	22
	2. FIELD TESTS	22
	3. DISCUSSION OF FIELD TEST RESULTS	26
	4. DATA REDUCTION PROCEDURE	27
	REFERENCES	29

LIST OF FIGURES

Figure	Title	Page
1	General Experimental Setup	10
2	Single Cylinder Efficiency versus Peclet Number for all Experimental Data	18
3	Composite Particle Diameter versus Penetration curves for 5, 10, 20 and 36 Screens	20
4	Composite Temperature versus Penetration curves for 5, 10, 20 and 36 Screens	21
5	Composite Flow Rate versus Penetration curves for 5, 10, 20 and 36 Screens	23
6	Effect of Number of Screens on Penetration at 27°C and 4 lpm	24
7	Effect of Number of Screens on Penetration at 260°C and 4 lpm	25

SECTION I

INTRODUCTION

A knowledge of aerosol mass distribution as a function of particle size is essential in design and selection of air pollution abatement equipment, evaluation of air quality criteria, health effects studies and numerous other applications. Direct measures of mass distribution often prove to be superior to indirect measures such as mass calculations based upon number, or surface area distribution measurements. Because particle chemical composition data are also frequently required, it is desirable to obtain size fractionated samples suitable for subsequent chemical analysis.

Interest in plume opacity, atmospheric visibility, and health effects of submicron aerosols is growing. Condensation aerosols are mainly of submicron size and frequently have mass median diameters as small as 0.1 μm. As a result they are of great current interest. These condensation aerosols are frequently volatile; therefore, their diameter depends on temperature and pressure. This implies that the measurement device must operate at the conditions at which the particles exist, so that no changes in the aerosol are induced.

A five stage, screen-type diffusion classifier has been developed for in-situ measurement of submicron aerosols at temperatures and pressures commonly encountered in industrial gas streams. It combines diffusion classification with mass measurement to permit direct mass distribution determination. This system has several advantages:

1. The diffusion classification technique is not fundamentally limited by temperature and pressure. The only constraints are the materials of construction.

2. Particle size classification measurements are not adversely affected by particles smaller than 0.01 μm because they make up only a very small fraction of the total particulate mass.

3. Mass distribution measurements are direct; they do not involve derivation from number or surface distributions. In the presently existing diffusion classifiers a condensation nucleus counter or an optical particle counter is used and number distribution is determined.

4. In-situ size classification data are obtained since particulate mass collection is done at the same conditions as size classification.

5. The effect of gas stream properties on particle size distribution can be studied.

6. The equipment is fundamental, simple and relatively inexpensive.

7. Evenly deposited samples over a large area are obtained, and these are suitable for direct chemical analysis by techniques such as x-ray diffraction.

The prototype diffusion classifier has been calibrated under various combinations of flow rate, particle size and temperature. These data have been analyzed and a general penetration function, which represents the performance of the diffusion classifier, has been obtained. The data collected are fully presented later in this report and the derivation of the penetration function is explained.

A program written by Knutson based on Twomey's non-linear iterative formula has been used in a slightly modified form, to calculate true particle size distributions from the basic measurements. The modification mainly involves replacement of the penetration function developed by Knutson with the more general penetration function which has been developed in this project. The data reduction procedure is more fully discussed in later sections.

In a later phase of this project several field tests were conducted at two industrial sites to study the field performance of the diffusion classifier. No serious instrument problems were encountered with the diffusion classifier and the capabilities of the instrument were clearly demonstrated.

SECTION II

CONCLUSIONS

An "in-stack" diffusion classifier was designed, constructed, laboratory calibrated and field tested. Particle collection characteristics of four diffusion classification elements containing 5, 10, 20 and 36 screens were thoroughly examined. From the large volume of calibration data obtained a generalized penetration function was obtained. Error analysis of this penetration function was performed with temperature, flow rate, particle diameter, wire diameter and screen opening size being the variables.

In agreement with observed experimental data, the most significant parameter affecting aerosol classification was particle diameter. From measurement error considerations it was estimated that the data accuracy limit is ± 10 percent. The developed aerosol penetration function was compared with equations for screens developed by other authors.

Each of the four sets of screens was studied under a variety of test conditions and the measured penetrations were compared with penetration curves calculated from the penetration function under the same set of conditions. A series of figures has been presented and, comparisons are quite good across a wide range of conditions. However, there is an unexplained effect at temperatures greater than 371°C (700°F) since the model is unable to properly simulate the sharp drop in penetration at about this temperature for the smaller particle sizes. There are also deviations on the order of 3 percent for the smaller particle sizes used with 36 screens. There seems to be a particular problem in concentration measurements when penetration is less than about 20 percent. The penetration function is quite accurate and can be applied over the complete experimental range except for temperatures greater than 371°C. This suggests that more work is needed in this region.

It was experimentally determined that aerosol type was of no major consequence but charge effects could be a problem for smaller particles. Independent verification of particle size was performed and temperature and flowmeter calibrations were frequently checked. Particle size, flow rate and temperature were within the error limits used in the penetration function error analysis procedure.

Field tests were conducted at an oil fired power plant and a jet engine test cell. No major design or operational problems were encountered and the diffusion classifier performed as intended. However, lack of proper pretest preparation, namely incorrect substrate conditioning, led to artifact formation and consequent poor data.

Preliminary work was done with a data reduction procedure based on Twomey's nonlinear iterative formula. It worked quite well for the set of field data tested. Some work was done with known input distributions, including monodisperse and polydisperse aerosol conditions. The program does not handle monodisperse aerosol data but works well with polydisperse aerosol data. Further work needs to be done with the program to improve its capabilities and precision; specifically, an error analysis must be performed.

In summary, the developed diffusion classifier performed as intended in the field. The calibration of screens was quite extensive but further study is required at temperatures greater than 371°C. Further field testing is required to evaluate the diffusion classifier "in stack" potential. Finally, the data reduction procedure requires further refinement, both in its capabilities and its precision.

SECTION III

APPARATUS AND EXPERIMENTAL PROCEDURES

A diffusion classifier was developed to obtain particle size distribution data at actual stack conditions. Because of inadequate theory, it was necessary to experimentally determine diffusion classifier performance in the laboratory under a wide variety of environmental conditions. The characteristics of the screens in the different diffusion stages were studied with the aid of various size monodisperse aerosols at various flow rates and gas temperatures. The general experimental procedures, and the diffusion classifier are described in this section.

1. DIFFUSION CLASSIFIER DESCRIPTION

The diffusion classifier uses fine-mesh screens for aerosol classification, as does the unit described by Sinclair and Hoopes (Reference 1). Five stages operate in parallel, each sampling at the same flow rate. Sampling rates are maintained by carefully matched critical orifices. When operated at a pressure drop of about 41 cm Hg the orifices go critical and provide a precalibrated maximum flow rate. Construction is of machined stainless steel throughout, with the five stages enclosed in a threaded 25 cm long by 7.5 cm outer diameter, cylindrical casing.

Of the five stages, four use different numbers of identical screen elements for differential particle size fractionation, while the fifth stage has no screens, so as to provide a total aerosol sample. The physical parameters of each set of screens, as used in experiments, were measured with a light microscope equipped with a stage micrometer. Each stage is provided with a highly efficient, low reactivity after-filter to collect the particles which penetrate the screens. By varying the number of screens the performance characteristics of each stage can be easily varied to suit individual needs.

When an aerosol passes through a set of screens, small particles are deposited on the screens by diffusion and the penetrating particles are collected on the after-filter for subsequent weight change determination and chemical analysis. The efficiency of large particle removal increases with the number of screens, resulting in lower mass penetration and smaller filter weight gains. The raw weights obtained then represent cumulative data.

Each diffusion classifier stage consists of two parts. The screens are placed in the top section and held in place by a retaining ring. The top

section has been designed to protect the screens from physical damage and to provide an open area of flow, of at least the same order of magnitude as the screen open area. The filter is placed in the bottom section and the diffusion classifier is now assembled as discussed in Appendix A. Data analysis and data reduction procedure are also discussed later.

2. AEROSOL GENERATION

a. Test Aerosols

The laboratory test aerosols used in this study can be broadly classified into two types: 1) liquid aerosols, and 2) relatively solid, hygroscopic aerosols. The liquid aerosols generated from solutions of dioctyl phthalate (DOP) in ethanol are generally spherical. The solid, hygroscopic aerosols generated from solutions of reagent grade sodium chloride in water are generally cubic. They were chosen to simulate a large cross section of aerosol streams which would be encountered in field applications of the diffusion classifier. These aerosols also permit a study of the dependence of diffusion classifier performance on the type of aerosol sampled.

DOP and sodium chloride solutions were atomized by a standard Collison atomizer. To generate monodisperse aerosols with $d_p \geq 0.1$ μm, solution concentrations of 5 percent sodium chloride and 2.5 percent DOP were used with the Collison atomizer operated at pressures of about 25 psi, and 10 psi, respectively. For monodisperse aerosols with $d_p < 0.1$ μm, solution concentrations of 1 percent sodium chloride and 1 percent DOP were used with the Collison atomizer operating at the same pressures as mentioned earlier. In general, higher pressures and less concentrated solutions were used in generating particle sizes less than 0.1 μm.

b. Collison Atomizer

The standard Collison atomizer was used to generate a polydisperse aerosol from which a monodisperse aerosol is fractionated. The atomizer was operated at a pressure of 10 to 30 psi, producing an aerosol flow of approximately 4 to 8 lpm.

The output of the Collison atomizer was found to be relatively stable over the period of the experiment when sodium chloride solutions were used. However, when DOP solutions were used the level of solution in the atomizer fell so rapidly that the output was quite variable. Since ethanol has a much higher vapor pressure than DOP, it will be consumed much faster than DOP in the atomizer. This was remedied by injecting a continuous stream of pure ethanol with a syringe pump, at a rate equal to the rate of loss of solution.

To cut down the polydispersity of the output aerosol, it was passed through a single stage impactor with an approximate cut size of 1 μm and then mixed with dilution air. Aerosol formation by atomization of solutions results in high electrostatic charges on particles which cause undesirable particle losses in sampling systems. This charged aerosol was neutralized

(brought to a state of Boltzmann equilibrium charge distribution) in a TSI Model 3054 Aerosol Neutralizer.

The Collison atomizer output was used as input to a Model 3071 Electrostatic Classifier to produce the monodisperse test aerosols required for calibration of the diffusion classifier.

c. TSI Model 3071 Electrostatic Classifier

The operating principle of the TSI Model 3071 Electrostatic Classifier is based upon a monotonic relationship between electrical mobility and particle size.

The significant features of the electrostatic classifier include a bipolar charger or "neutralizer" and a differential mobility analyzer. The TSI Model 3077 Bipolar Charger is a device which contains two millicuries of Kr-85. This radioactive source ionizes the surrounding gas, producing bipolar gas ions. These ions impart a Boltzmann equilibrium charge distribution to the incoming aerosol. When this equilibrium state is reached a known percentage of the gas borne particles have either no charge, one charge, or various multiple charges. This aerosol is then passed into the differential mobility analyzer for fractionation.

The analyzer is in the form of two concentric cylinders. The neutralized aerosol passes through the annular space between the two cylinders. The inner cylinder is the collector rod to which a negative dc voltage is applied while the outer cylinder is grounded. The collector rod thus attracts positively-charged particles, the particles with higher mobility being precipitated higher up the rod. Only those particles with the right mobility will pass through the sampling slit.

The classifier was used to generate monodisperse aerosols with sizes up to, and including, 0.2 μm. The classifier was operated in the overpressure mode and, to increase the volume of aerosol, the monodisperse aerosol stream was mixed with clean, dilution air in a mixer.

The performance of the classifier depends on the quality of the input aerosol: the less polydisperse the input aerosol, the more monodisperse the output aerosol. Since the mobility analyzer classifies particles by mobility, if the input aerosol contains a large number of large particles, then the classifier output will contain larger, multiple-charged particles with the same electric mobility as the smaller singly-charged particles which are desired. This error can be significantly reduced by using a single stage impactor and a heater-condenser section and by selection of an appropriate solution concentration, although this problem is significant only for particles greater than approximately 0.1 μm.

The classifier was used to generate monodisperse DOP and sodium chloride aerosols in the 0.03 μm to 0.2 μm particle diameter range and concentrations obtained were in the order of 10^4 to 10^5 particles/cm^3.

3. PENETRATION MEASUREMENT

a. TSI Model 3030 Electrical Aerosol Analyzer

The TSI Model 3030 Electrical Aerosol Analyzer (EAA) is similar to the Model 3071 Electrostatic Classifier. In addition to the differential mobility analyzer, the EAA has a unipolar charger instead of a bipolar charger. Analyzer design and operating characteristics are discussed in References 2, 3, and 4.

The input aerosol to the EAA must be neutralized. The unipolar diffusion charger puts positive charges on the neutral aerosol particles. When these charged aerosols pass into the mobility analyzer, all particles that are not deposited are detected by an electrometer current sensor. By varying the precipitating voltage on the collector rod, the analyzer current can be measured and through a data reduction procedure discussed by Liu et al. (Reference 3), concentration of an aerosol and the corresponding size distribution can be determined. This voltage can be varied manually, or automatically by means of a control package with preset voltage steps.

As mentioned earlier, the input aerosol to the EAA must be neutral and hence the output from the electrostatic classifier must be neutralized before input into the EAA. Since a monodisperse aerosol was being input, of the eleven channels in the EAA , only the immediately relevant channels were used. However, most of the data was obtained with the aerosol electrometer which will be described in the next section.

b. TSI Model 3068 Aerosol Electrometer

The TSI Model 3068 Aerosol Electrometer is not a size spectrometer like the EAA and its capabilities are limited to total concentration measurement.

It consists basically of an absolute filter connected to an operational amplifier. When charged particles are deposited on the filter, the discharge current is measured, amplified, and output as a voltage between 0-10 V, corresponding to a current between 0-10 picoamps. This current is related to the particle concentration. Thus, if the charge of the input particles is known, their concentration can be determined.

If a neutral aerosol is input, as is done with the EAA, no current will be measured since the number of positively and negatively charged particles are equal. This unit can operate with a maximum pressure drop of 22 cm of water and flow rates up to 10 lpm. It was very convenient to use in the calibration procedure, as it could be operated at a variable flow rate. If concentrations are to be calculated, a correction factor must be applied to the measured current to account for the excess current produced by the collection of larger, multiple-charged particles with the same electric mobility as the smaller, singly charged particles desired. The ratio of the measured currents, with and without screens, for a given monodisperse aerosol, represents the fractional penetration of the aerosol through the screens.

4. TEMPERATURE AND FLOW RATE MEASUREMENT

The calibration of the diffusion classifier was done at temperatures up to 482°C(900°F). This required careful measurement of temperature. A type K grounded junction thermocouple with an inconel sheath was plumbed into the sampling system inside the oven to sense the temperature of the aerosol stream.

A Compact Portable Potentiometer, manufactured by James G. Biddle Co. was used to measure the EMF generated by the thermocouple, and the corresponding temperatures were determined from reference tables.

The second variable in the calibration procedure was flow rate. The electrostatic classifier, EAA and aerosol electrometer were all equipped with mass flowmeters. They sense the mass of air flowing past the sensor and are temperature compensated. These flowmeters were always operated at temperatures close to ambient by passing the output aerosol from the diffusion classifier stage being tested in the oven, through a water cooled heat exchanger. The equivalent flow rates at which the flowmeters had to be set to obtain a flow rate of 2, 3, 4, or 5 lpm at actual conditions were calculated from the General Law of Gases. When the aerosol electrometer was used these various flow rates were set directly on the instrument. When the EAA was used, the available sensitivity factors fixed the aerosol flow rate at 4 lpm and thus clean air was either pumped in, or excess aerosol pumped out of a tee just before the EAA depending on whether the required flow rate at actual conditions was less than or greater than 4 lpm. The EAA aerosol flow rate, the actual flow rate in the diffusion classifier stage, and the rate of excess aerosol to be pumped out, or clean air to be pumped in at the tee, are related.

5. EXPERIMENTAL SETUP

The basic experimental setup involved equipment for the generation of reproducible test aerosols of a variety of materials, means for measuring penetrations through a set of screens, flow control and measurement devices, clean air supply, and an oven capable of providing temperatures of at least 540°C (1000°F). The general arrangement was as shown in Figure 1.

The building's compressed air was purified by passing it through an oil filter and a dryer. This was then split into two streams, each controlled by regulators and followed by absolute filters. One stream was used as the sheath air supply for the TSI Model 3071 Electrostatic Classifier. The other stream was used to provide a metered supply of dilution air and also to operate the Collison atomizer. A syringe pump was used to supply a constant feed of ethanol when a DOP solution was atomized, to maintain the level of the solution and to keep the concentration relatively constant over a long period of time. The output of the atomizer was passed through a single stage impactor with a cutpoint of 1 μm to remove any large particles and droplets and thus cut down the polydispersity of the aerosols. The output from the Collison atomizer was then mixed with dilution air and passed through a charge neutralizer. The dilution air was supplied in the

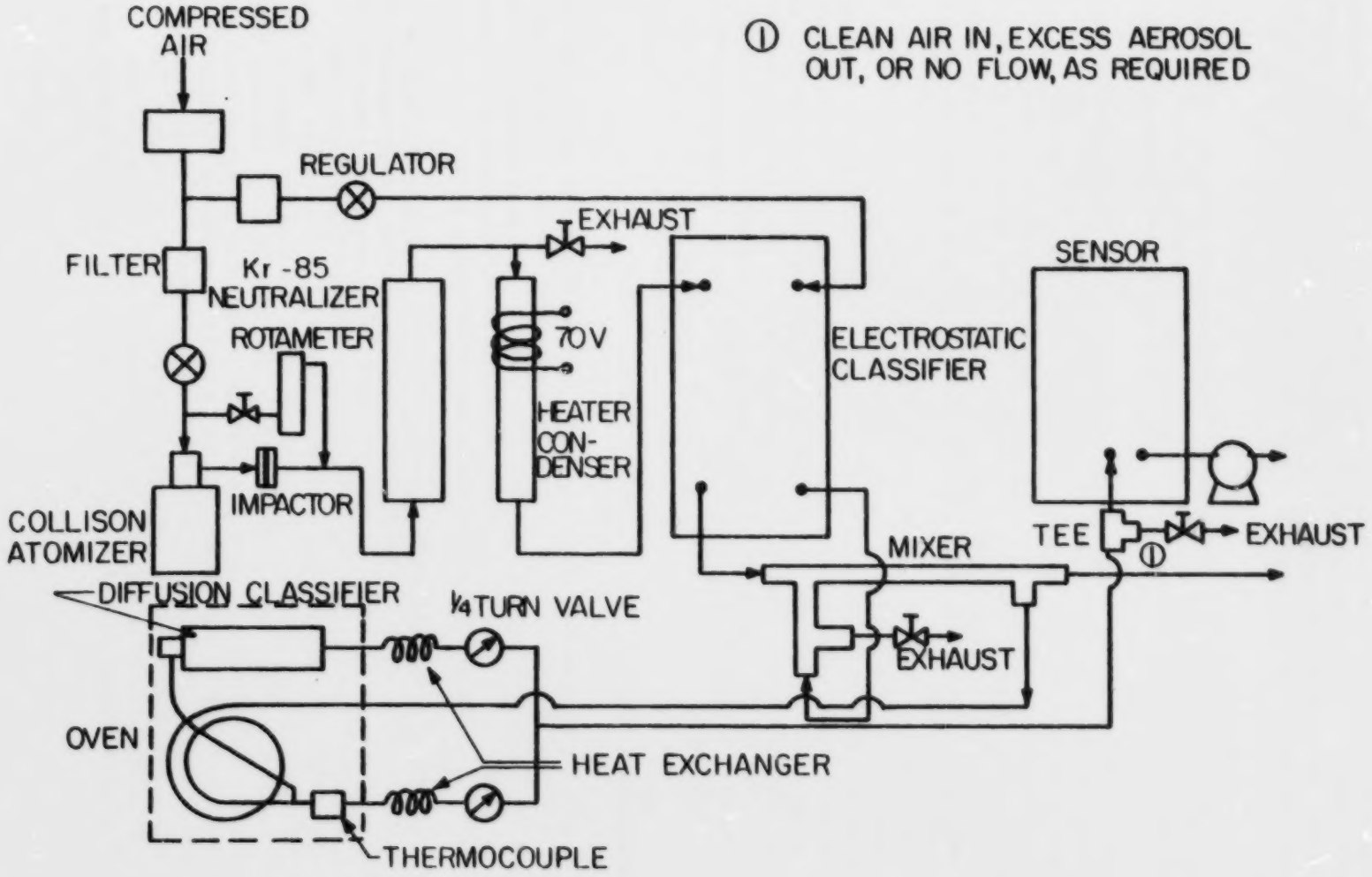

Figure 1. General Experimental Setup

approximate ratio of 4:1 with respect to the aerosol stream to provide proper conditions for droplet evaporation, while the Kr-85 charge neutralizer was used to return the aerosol to a Boltzmann equilibrium charge distribution from the highly charged condition created by the atomization process.

The output from the neutralizer was partially exhausted and the remaining aerosol was passed through a heater-condenser section. Here, due to the vaporization process, the larger multiple-charged particles reach the Rayleigh limit and become mechanically unstable, thus splitting into two or more smaller particles with one or two charges on them. This produces a less polydisperse aerosol which is input into the TSI Model 3071 Electrostatic Classifier to produce monodisperse aersols. The monodisperse aerosol is mixed with a controlled flow of dilution air, obtained as excess air from the electrostatic classifier, in a mixer.

The aerosol was sampled through a stainless steel heat exchanger into the diffusion classifier stage being tested, the assembly being placed inside an oven. The temperature of the heated aerosol stream was measured by a thermocouple-potentiometer arrangement. A bypass system was also constructed so that alternating measurements could be made with and without screens in the aerosol stream to be able to calculate penetrations. This aerosol stream was then cooled in a water cooled heat exchanger and sampled either by the Model 3068 Aerosol Electrometer or by the Model 3030 EAA, depending on whether the aerosol was charged or uncharged. The specific area of application will be described later in this section. When the EAA was used, clean air was pumped in or excess aerosol pumped out at a tee just before the EAA aerosol inlet, depending on whether the actual flow rate required in the diffusion classifier stage was less or greater than 4 lpm.

6. EXPERIMENTAL PROCEDURE

The calibration procedure involved generation of monodisperse aerosols with diameters between 0.03 μm and 0.20 μm and studying their penetration through various sets of screens, with flow rate and temperature being 2 other variables. The flow rates which were used were 2, 3, 4, and 5 lpm, and the temperatures used were 27°, 149°, 260°, 371°, and 482°C. (80°, 300°, 500°, 700°, and 900°F).

Since such a wide range of test conditions were to be used in the experiments, an optimum operating method was developed to make data collection more convenient and less time consuming. To decide on the number of screens to be used in the 5 stages for further study, the following procedure was followed: stage #5 had no screens and in effect represented the total aerosol. For stage #4 the number of screens was chosen so that the penetration of the 0.03 μm diameter particle was approximately 50 percent. The same method was followed with the other stages for 0.05 μm, 0.10 μm and 0.20 μ diameter particles. The number of screens used were, thus, 0, 5, 10, 20 and 36, respectively.

Once the 4 sets of screens were decided on, each individual set was tested. A chosen set of screens was mounted in the diffusion classifier stage and left in place until a complete series of tests was run. At 27°C and 260°C the flow rate and particle size were varied while at the other temperatures the flow rate was fixed at 4 lpm and the particle size was fixed at the size which had an approximate 50 percent penetration for the given set of screens at 27°C.

Initially, data were not taken with 0.03 μm particles because of certain problems which will be discussed later in this section. For each setting of a combination of flow rate, particle size, number of screens and temperature, a minimum of 6 penetration measurements were made during a particular experiment and this experiment was, in most cases, repeated on at least 2 other days. The procedure was performed on at least 3 separate occasions to check the repeatability of the experiment and to have statistically valid data.

Sodium chloride aerosols were used for all high temperature work. For work at ambient temperatures both DOP and sodium chloride aerosols were used. The chosen solution was atomized in the Collison atomizer at pressures between 10 and 30 psi depending on the experiment. If a DOP solution was used, the syringe pump was used to pump pure ethanol into the Collison atomizer at the same rate as the rate of loss of solution. The heater in the heater-condenser section was arbitrarily set at 70V. This seemed to heat the aerosol stream enough to cause solvent vaporization from particle surfaces. The aerosol stream was now passed into the eletrostatic classifier; clean, regulated sheath air was also input to the electrostatic classifier. The four air flow paths in the electrostatic classifier were set such that the sheath air and excess air flows were both 20 lpm, and the polydisperse aerosol and monodisperse aerosol flows were equal and between 3 and 4 lpm. The monodisperse aerosol and excess air flows were mixed, and a vacuum pump drew the sample aerosol through the diffusion classifier stage and then through the aerosol electrometer where the aerosol concentration was measured.

When experiments were conducted with 0.03 μm particles the EAA was used in place of the aerosol electrometer. The output from the electrostatic classifier was passed through a Kr-85 charge neutralizer and, then through the diffusion classifier stage, to the EAA. The rest of the system remained unchanged, except for the flow system just before the EAA. This has been described earlier in this section.

This system was run for about 10 minutes before any data was collected. After the required data was obtained at 27°C, the temperature of the oven was raised to 149°C, the flow in the diffusion classifier stage was adjusted to the actual flow required, and penetration measurements were made. This process was followed at the other temperature settings except at 260°C where runs were performed similar to those at 27°C. After this series of experiments was completed the diffusion classifier stage was allowed to cool off, and the whole series was repeated with a new set of screens.

7. SPECIAL CONSIDERATIONS

The test procedure has been described in detail in the previous subsection. The calibration system and procedure discussed resulted from a series of refinements to the original test system. Various checks on the system were performed as described below before data collection was begun.

Patterson and Calvert (5) have used spacers between diffusion screens to provide adequate aerosol mixing between screens. To check on the necessity for using spacers an experiment was performed to compare results when screens were used: 1) without spacers, 2) with 0.0025 cm thick spacers, and 3) with 0.0084 cm thick spacers. Data show that the analyzer currents and the resulting aerosol size distributions are comparable. Therefore, it was concluded that spacers were not necessary in the calibration of sets of screens in the diffusion classifier stages.

Since both the EAA and the aerosol electrometer were to be used in the experiments a comparison of their capabilities was made, with regard to total aerosol concentration and size distribution measurement. A solution was atomized and passed through the electrostatic classifier. Various sizes of monodisperse aerosols were produced and sampled with both the EAA and the aerosol electrometer. Though the size distributions measured were almost identical, the total concentration measured by the EAA was about 20 percent lower than that measured by the aerosol electrometer under identical conditions. However, since the variable of interest was penetration, and not concentration, this problem was not of great concern.

Once the system was completely assembled it was leak tested at about 5 psi and found to be almost leak-proof. In the first version of the sampling system the total length of Polyflow tubing between the electrostatic classifier, the diffusion classifier stage being tested and the aerosol electrometer was about 10m. Excessive losses were found to occur, which could not be explained by diffusive deposition. Other possible sources of losses considered were loss of charge on particles, space charge deposition, and build up of static charges on Polyflow tubing. Individual experiments were run and calculations performed to check the effect of these mechanisms but the results obtained showed that these loss mechanisms were not significant enough to explain the measured loss. Experiments were also conducted in which 0.03 μm and 0.1 μm sodium chloride aerosols were passed through 5 meters of copper tubing and 5 meters of Polyflow tubing in parallel and sampled with the EAA and the aerosol electrometer. Results indicated that due to some as yet undetermined mechanism, the loss of 0.03 μm particles through the Polyflow tubing was almost 95 percent while the loss for the copper tubing was about 40 percent. The corresponding losses for the 0.10 μm particles were 20 percent and 3 percent, respectively. It was thus decided to reduce the length of Polyflow tubing used and to use copper tubing where possible.

Sinclair et al. (Reference 6) have studied the effect of single charges on particles passing through screens. They concluded that image force attraction caused significant losses of 0.024 μm, singly charged sodium chloride aerosols. An experiment was conducted with 0.03 μm, 0.05 μm and

0.10 μm monodisperse aerosols, generated by the eletrostatic classifier, passed through 10 screens at 4 lpm and it was found that charge had no significant effect on penetration with 0.05 μm and 0.1 μm aerosols but with 0.03 μm aerosols there was a significant effect. Thus it was decided to neutralize 0.03 μm aerosols and to use the EAA for measurement of penetration. The larger particles, however, could be used in the charged condition and thus could be measured with the aerosol electrometer.

Since the mass flow meter in the aerosol electrometer measures flow in equivalent standard lpm, the flow setting was such that a volume of sample at standard conditions would expand to the required volume at actual conditions. This has been more fully discussed in an earlier subsection.

Figure 1 schematically shows the general experimental setup. It will be observed that there are two parallel flow paths between the electrostatic classifier and the particle sensor (EAA or aerosol electrometer). One path is a bypass while the other path includes the screens being tested; these screens are mounted in a diffusion classifier stage. In the following experiments the diffusion classifier stage was operated without screens. Aerosols of various sizes were passed through both paths, and the measured current due to particle penetration was compared. It was found that the two flow paths performed identically for all particle diameters larger than 0.05 μm. For 0.05 μm particles a 3 percent loss was observed in aerosol penetration through the flow path containing the diffusion classifier stage. For 0.03 μm particles a 5 percent loss was observed. This effect has been considered in data analysis.

SECTION IV

FIELD TESTING

Laboratory aspects of the use of the diffusion classifier have been thoroughly discussed in the previous section. However, in the laboratory calibration only one stage was tested at a time and conditions were well controlled. In the field testing procedure the diffusion classifier was assembled and tested at two locations: Jacksonville Electric Authority (J.E.A.), Southside Generating Station, Unit #4 (oil-fired boiler) and the Naval Air Rework Facility, Jet Engine Test Cell #11 (J-52 engines).

1. TEST PROCEDURE

The intention behind the field test procedure was to study the performance of the diffusion classifier under hostile conditions and to identify and correct any operational problems. The EPA Method 3 procedure for the determination of particulate emissions from stationary sources was used, with slight modifications, in both test locations.

Velocity and temperature traverses were first obtained with an S-type pitot tube and direct read out thermocouple, respectively. The diffusion clasifier was always preceded in the sampling system by either a Washington Mark III Cascade Impactor, or an Andersen Mark III Cascade Impactor to size fractionate particulate matter larger than about 0.4 μm and prevent overloading of the diffusion classifier stages. Since only one set of calibrated critical orifices was available at the time of the field test the sample flow rate was fixed. Thus, to maintain approximately isokinetic conditions the correct sampling nozzle was chosen. The rest of the system consisted of the probe, which was hooked to the condenser by an umbilical cord, and the sampling box.

Before a sample was drawn from the stack, the diffusion classifier and cascade impactor were left in the stack for about 30 minutes, with the nozzle inlet plugged, to reach temperature equilibrium with the stack gas. Thirty or sixty minute samples were then taken. Prior information revealed that the fraction of particles larger than 1 μm was not high and thus no problem with overloading of the impactors was expected.

The impaction plate and the diffusion classifier filter weight gains were measured with a Cahn Model 4700 Automatic Electrobalance. From the weight and flow rate data the particle size distribution was determined.

2. SPECIAL CONSIDERATIONS

Two types of impaction surfaces were used: glass fiber substrates and stainless steel substrates with Apiezon H coatings. In the diffusion classifier two types of filters were used: glass fiber and teflon. The glass fiber and coated stainless steel substrates were heated to 149°C and dessicated until ready for use.

For submicron aerosols, isokinetic sampling is not essential. However, every effort was made to obtain an isokinetic sample. In the Southside Power Plant it was not a problem but at the Jet Engine Test Cell, the nature of the jet engine testing procedure made it impossible to obtain an isokinetic sample. Another related problem was that of stack characteristics. The Jet Engine Test Cell had noise abating baffles at the outlet of a very short stack. As a result the velocity distribution was very haphazard and single point sampling was performed.

It was mentioned previously that the substrates were preheated to 149°C. However, at the Jet Engine Test Cell the temperatures exceeded 200°C, causing an expected weight loss from grease vaporization in the case of the coated stainless steel substrates. The Southside Power Plant stack gas contained significant amounts of sulfur oxides. Since the glass fiber filters were not conditioned in such an environment it was expected that artifact formation would seriously bias the glass fiber filter weight gains, but not with the teflon filters.

The results obtained and the effects of the test variables are discussed in the next section.

SECTION V

RESULTS AND DISCUSSION

Results of laboratory and field tests are presented. The development of a semi-empirical penetration function is discussed and the function is compared with other relationships presented earlier. Field test data are analyzed and their validity assessed.

1. LABORATORY TESTS

a. Development of Semi-Empirical Penetration Function

Among the primary intentions of this project was to develop a generalized penetration function which could be used to predict the performance of each stage of the diffusion classifier at any combination of temperature, flow rate and particle size. This would make the diffusion classifier compatible with field sampling in non-standard environments.

Experimentally determined penetrations for various conditions were converted to equivalent single cylinder efficiencies η_D. Also, for each of these conditions, the Peclet number, N_{pe}, was calculated. To determine the functional relationship, g, between η_D and N_{Pe}, these two variables were plotted as shown in Figure 2. This suggested a linear relationship on the log - log plot. By applying a power curve fit in a HP - 97 programmable calculator the straight line plotted in Figure 2 was obtained with $r^2 = .98$. The equation of this line is

$$\eta_D = 4.3\ (N_{Pe})^{-0.59} \tag{1}$$

and the corresponding penetration function is

$$P = \exp\ (-4.3n\ S(N_{Pe})^{-0.59}) \tag{2}$$

or, for the nominal 635 mesh screens used in this project,

$$P = \exp(-3.0ln\ (N_{Pe})^{-0.59}) \tag{3}$$

b. Effect of Particle Size on Penetration

Each of the 4 sets of screens mentioned earlier was tested. At 27°C (80°F) and 260°C (500°F), 0.03, 0.05, 0.07, 0.10, 0.15 and 0.20 μm diameter

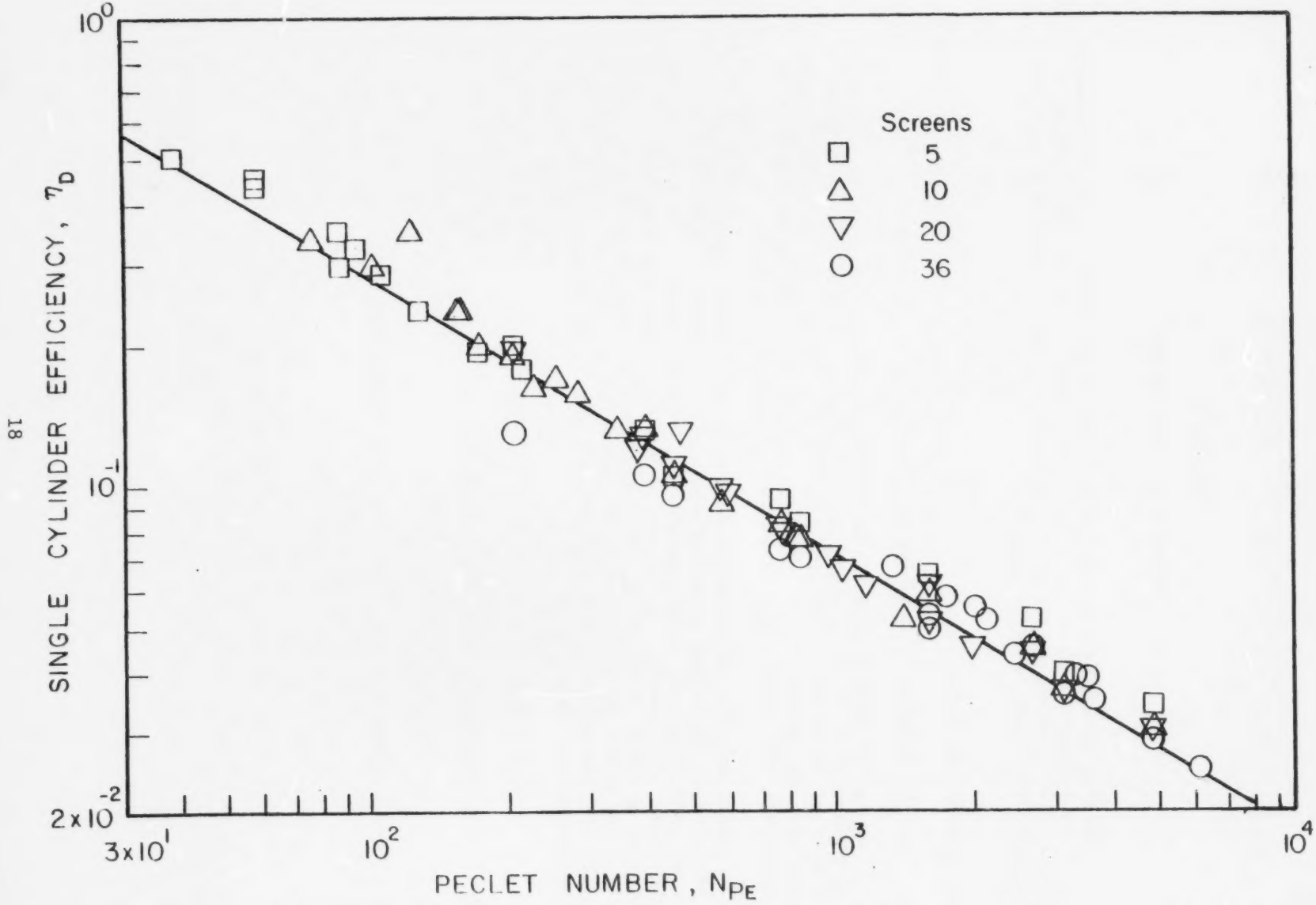

Figure 2. Single Cylinder Efficiency versus Peclet Number for all Experimental Data

monodisperse aerosols were used at a flow rate of 4 lpm. Penetration increased with particle size for a given set of screens and for a given particle size penetration was lower at 260°C than at 27°C. The penetration curves become steeper with increasing number of screens. Figure 3 shows this data in a convenient form. The experimental data have been plotted over curves generated from the semi-empirical penetration function. There is very good agreement between the penetration function and experimental data for 5, 10 and 20 screens for both 27°C and 260°C and there seems to be a constant difference of about 4 percent in penetration for particle sizes less than 0.15 μm for 36 screens.

c. Effect of Temperature on Penetration

As before each of the 4 sets of screens was tested, the approximate d_{p50} of each set of screens at 27°C was used in testing each set of screens at each of the temperatures; i.e. use 0.05 μm diameter particles with 10 screens at variable temperature. The test flow rate was 4 lpm. As would be expected from theoretical considerations, penetration decreases with increasing temperature (Figure 4). The rate of decrease of penetration is almost identical for 5, 10, and 20 screens where, respectively, 0.03, 0.03 and 0.10 μm diameter monodisperse aerosols were used, though the rate is slightly lower for 0.10 μm diameter particles. However, with the 0.20 μm diameter monodisperse aerosols and 36 screens, the rate of decrease is signficiantly lower. This also agrees with theory as can be seen from the data in going from 27°C to 260°C, for example, the diffusivities, which are inversely proportional to penetration, increase by 85 percent, 105 percent, 122 percent, and 128 percent for 0.20, 0.10, 0.05 and 0.03 μm diameter particles, respectively. Thus, 0.2 μm particles are less severely affected by temperature and penetration is higher.

Agreement between experimental data and the semi-empirical curve fit is reasonably good in all cases up to about 371°C (700°F). The set of composite curves in Figure 4 show a sudden drop in penetration around 371°C (700°F) for particle diameters less than 0.2 μm, and this is not simulated well by the model. More work needs to be done at this temperature to study in greater detail the particle and fluid mechanics at such elevated temperatures.

d. Effect of Flow Rate upon Penetration

As in the case of the temperature variation experiments, the same sets of screens and particle sizes were used. However, only 2 temperature conditions, 27°C and 260°C were used with various flow rates. These data are shown in Figure 5. As previously discussed, the difference in the penetration curves at 27°C and 260°C is not as much with the 0.2 μm diameter particles as with the smaller particles.

Agreement between the experimental data and the semi-empirical penetration function is good for most of the 27°C data. For 260°C data the agreement is only fair and there is an error of approximately 3 percent between the experimental points and the model. The experimental points are

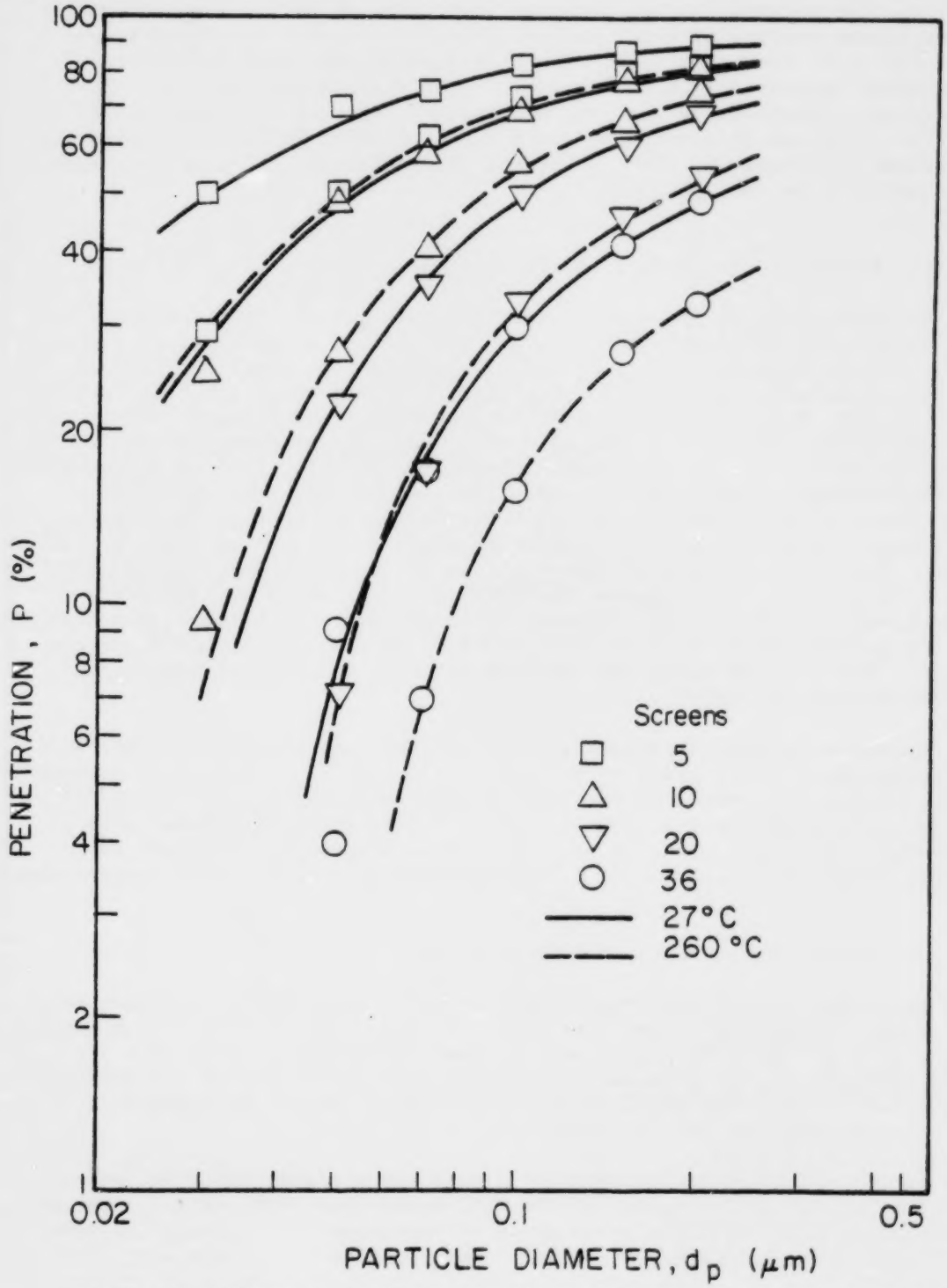

Figure 3. Composite Particle Diameter versus Penetration curves for 5, 10, 20 and 36 Screens

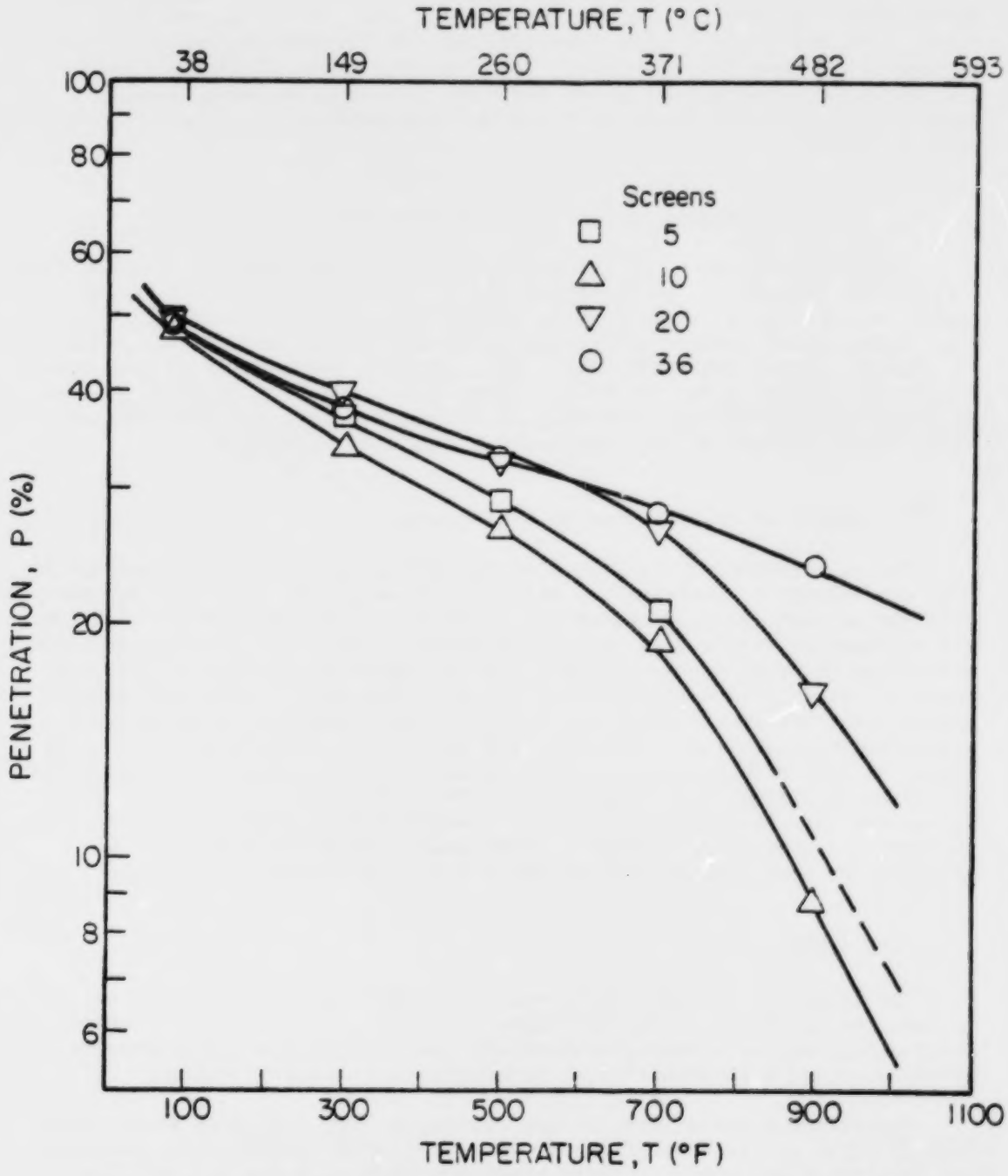

Figure 4. Composite Temperature versus Penetration curves for 5, 10, 20 and 36 Screens

consistently higher or lower than the model. This implies a consistent error in measurement. However, since the penetration function is the result of a power curve 'best fit', it is expected that the experimental points would deviate a bit from the curve fit. This has also been previously discussed. The composite experimental curves for flow rate as a variable, Figure 5, seem to indicate some as yet undetermined inconsistency for the 5 screen data at 260°C.

e. Effect of Number of Screens on Penetration

Figure 3 of P versus d_p for the 4 sets of screens has been redrawn from a different perspective as Figures 6 and 7, which are plots of P versus number of screens, n, with d_p as a variable. This figure also indicates that experimental results are in agreement with theory and the data with 5, 10, and 20 screens are quite good. But, for 36 screens there is some inaccuracy for smaller particle sizes. There seems to be a particular problem in measuring penetrations less than 25 percent for both the 27°C and 260°C cases for 36 screens at the experimental flow rate of 4 lpm.

f. Effect of Aerosol Type on Penetration

The calibration of the stages of the diffusion classifier would not be complete without a check for the effect of aerosol type on screen performance. Thus DOP aerosols were generated and exactly the same experimental procedure was followed as with sodium chloride aerosols. Data were obtained with DOP and sodium chloride aerosols, under similar operating conditions, for the cases of variable particle size and variable flow rate. From this data it appears that DOP penetrations are a little lower than that observed with sodium chloride aerosols. However, DOP aerosol concentrations were not as stable as with soduim chloride aerosols and this is probably the reason for the observed difference. From the available data, and its accuracy, this author believes that aerosol type, as studied, has no significant effect on diffusion classifier performance. More work needs to be done with DOP aerosols, to test more accurately the validity of the above conclusion.

2. FIELD TESTS

The intention of these tests was not to measure size distribution, but to test the operation of the diffusion classifier in hostile environments. Certain data analysis considerations will now be discussed in greater detail while the field test results will be presented in a later section.

Temperatures encountered at the Jet Engine Test Cell were about 230°C (450°F) while at the Power Plant it was about 149°C (300°F). The corresponding flow rates per stage at these conditions were 4.25 lpm and 3.46 lpm, respectively. At that time, no procedure for data handling and manipulation was available. Thus, a rather crude method was employed. It was assumed that a diffusion parameter, similar to that for the circular tube type diffusion classifier, could be defined for a given set of screens. It was

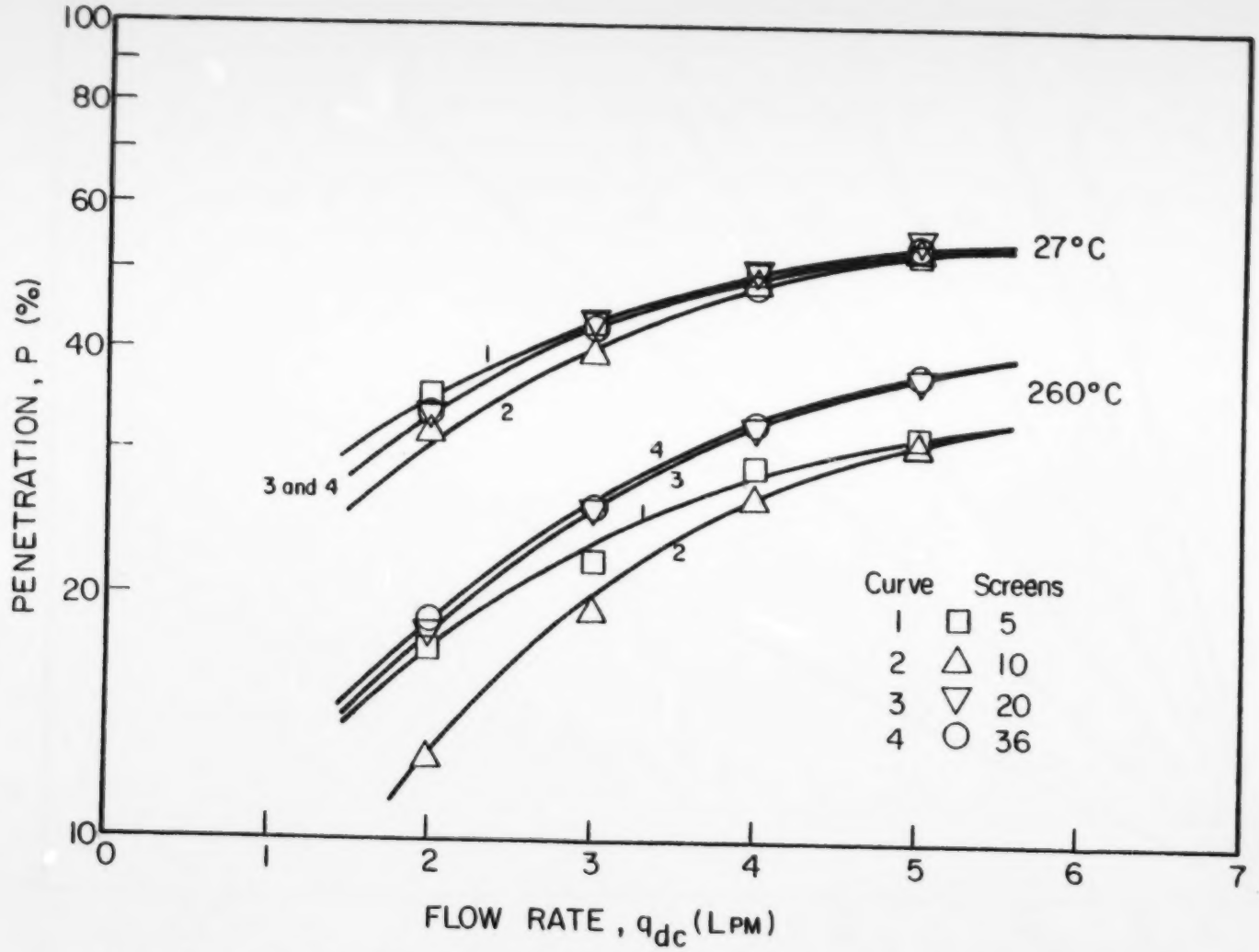

Figure 5. Composite Flow Rate versus Penetration curves for 5, 10, 20 and 36 Screens

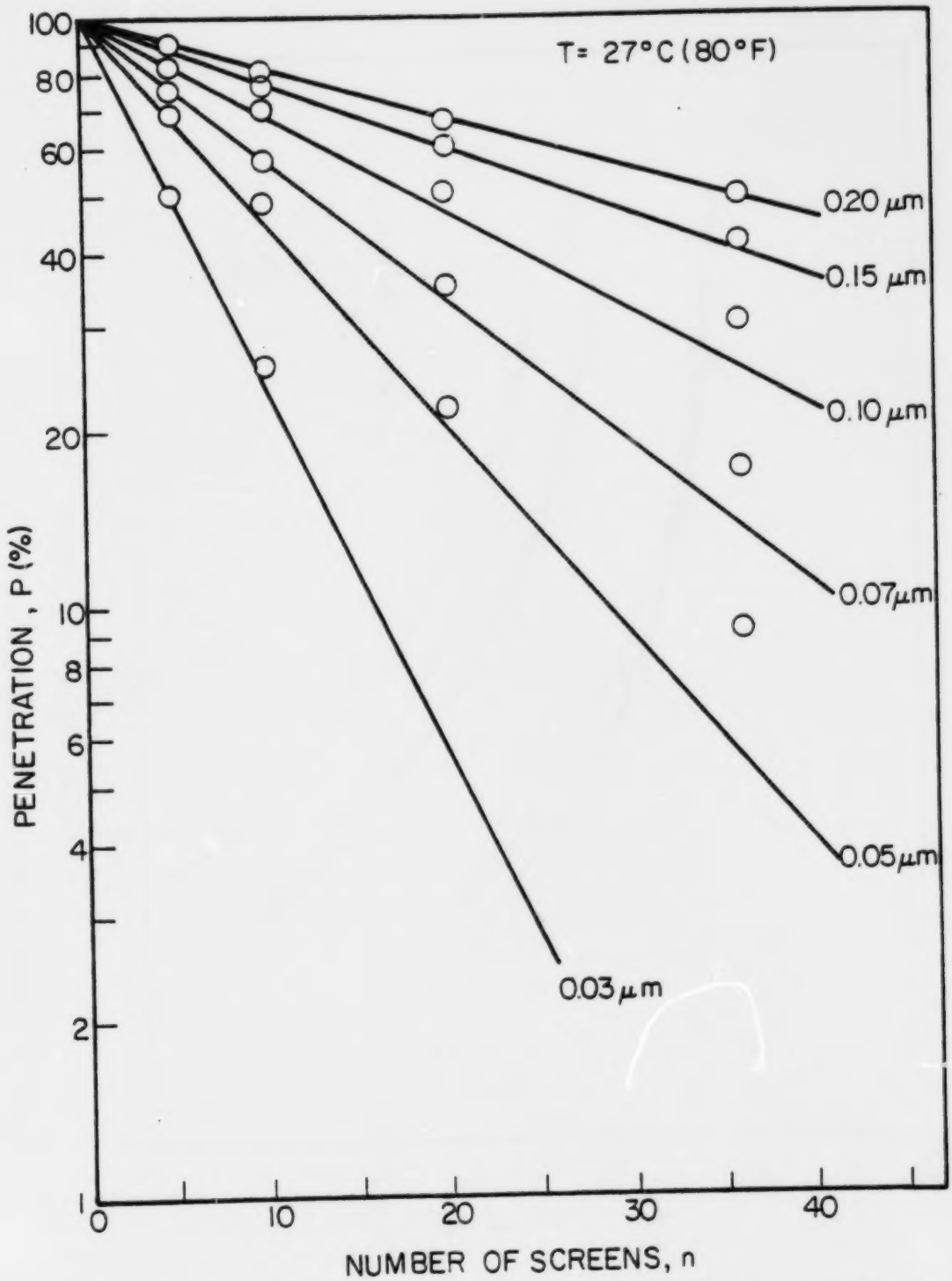

Figure 6. Effect of Number of Screens on Penetration at 27°C and 4 lpm

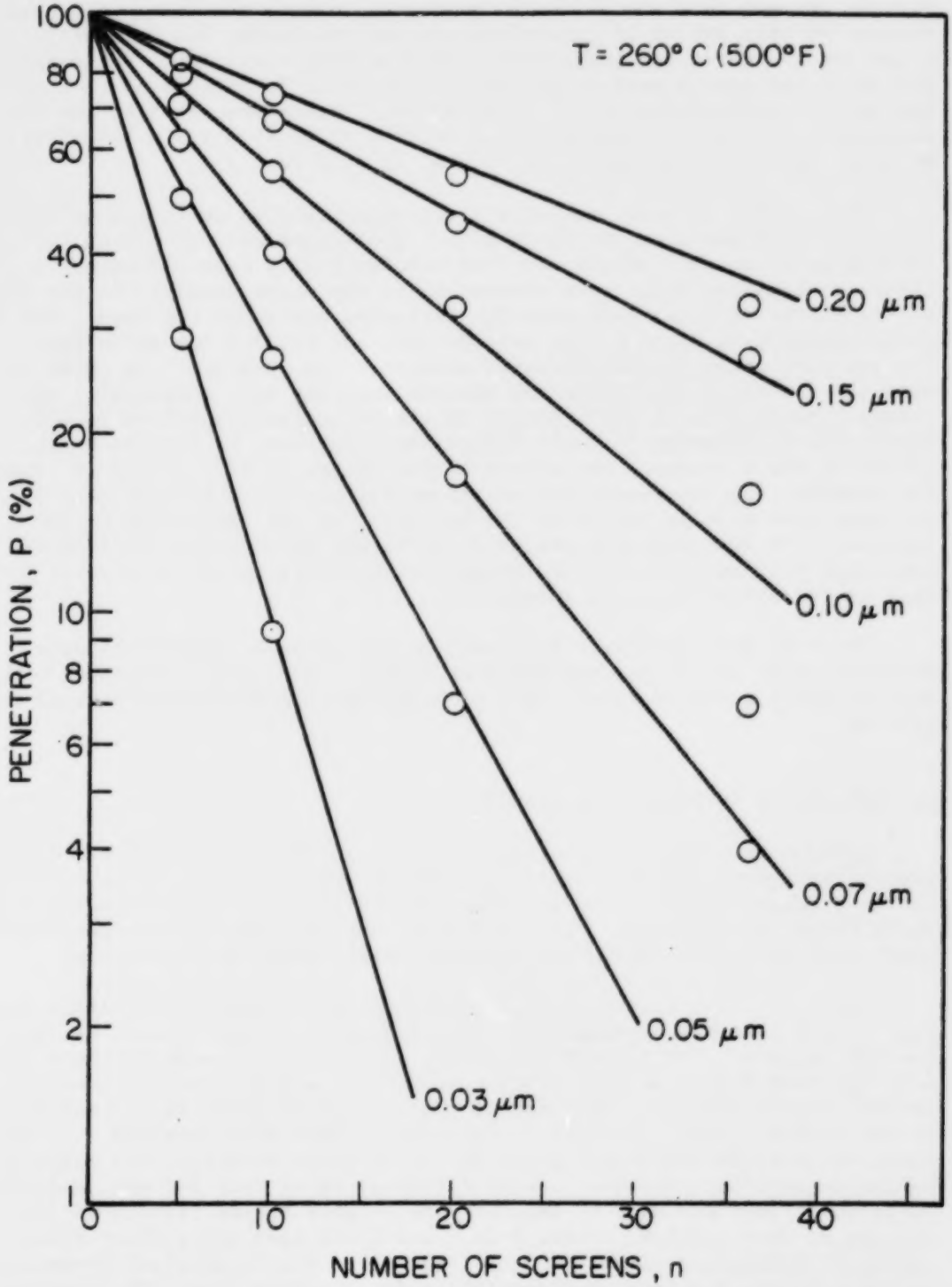

Figure 7. Effect of Number of Screens on Penetration at 260°C and 4 lpm

further assumed that the diffusion parameter remains constant. Since calibration at this set of of conditions was not available, the data at 27°C and 4 lpm was corrected for temperature and flow rate variation. For example, 0.2 μm is the approximate 50 percent cut point of 36 screens at 27°C and 4 lpm and its diffusivity is $2.2 \times 10^{6} cm^2/sec$. Therefore, at 3.46 lpm the diffusivity, D, is calculated as $2.2 \times 10^{6} \times (3.46/4) = 1.9 \times 10^{6} cm^2/sec$. By trial and error, d_p can be calculated as 0.27 μm.

This method is used just as a first approximation so that some conclusions can be drawn from the field data. The 50 percent cut points for the cascade impactor were determined from manufacturer's data and weight fractions in each size range were determined in the usual manner. In the case of the diffusion classifier data the following procedure was used. The flow rate through each stage of the cascade impactor is 17.3 lpm while that through each stage of the diffusion classifier is 3.46 lpm. In order to make the diffusion classifier and cascade impactor data compatible, the volume through each of the 5 stages in the diffusion classifier is multiplied by 5, assuming that all stages are identical, as are the weights gained in the 5 stages. The weight on the filter after a set of 36 screens, for example, now represents the weight of all particles greater than 0.27 μm but less than 0.38 μm, which is the cut point of the last stage of the impactor. To determine the weight of particles greater than 0.14 μm but less than 0.27 μm, subtract the weight on the filter after 36 screens from that on the filter after 20 screens.

The same data have also been analyzed by using a computer program provided by Dr. E. O. Knutson based on Twomey's nonlinear iterative formular in a slightly modified form. This program has been discussed later in this section.

3. DISCUSSION OF FIELD TEST RESULTS

Before the field test program a series of laboratory tests was conducted with polydisperse sodium chloride and DOP aerosols with and without screens in the 5 stages of the fully assembled diffusion classifier so that a comparative study could be made. It was obvious that all the five stages compare quite well with each other when operated under identical conditions.

Tests S-2, S-5 and S-7 were invalidated by problems like filters sticking to back plates and unexplained weight loss in various stages of the cascade impactor. In Tests S-6 and S-7, an attempt was made to check for artifact formation. In test S-6 a composite of a glass fiber filter and a teflon® filter was made, and used so that the glass fiber filter was upstream of the teflon filter. In Test S-7 the two filters were reversed. It was hoped to separate the weight gains due to artifact formation and particulate matter deposition. However, due to filter sticking Test S-7 was invalidated, while no attempt was made to separate the weights on the filters in Test S-6 because of this problem. Tests S-1, 3 and 6 all used glass fiber filters and there definitely seemed to be a large error due to artifact formation, as shown by the histogram and cumulative distribution plot. The problem mentioned above is confirmed in Test S-4. In this test teflon® filters were

used and weight gains are much lower and the results are much better. This was the only good test at the Southside generating station. It appears that the distribution is bimodal with the mode in the large particle range being very broad.

From the cumulative distribution plot of Test S-4 data the MMD is about 0.4 μm and the the σ_g is about 30 across the total distribution. This is not strictly correct because of the bimodality in the distribution. In using the computer program for data reduction the impactor and diffusion classifier data were treated separately. The MMD and σ_g of the diffusion classifier data, representing the small particle range, are 0.068 μm and 1.9, respectively. The corresponding values for the impactor data were 5.2 μm and 6.76. However, the full capabilities and limitations of this program have not been studied and, as such, the results must be considered no more than qualitative.

Poor data were obtained at the Jet Engine Test Cell because of losses in the greased impactor substrates from temperature excursions beyond those expected. Artifact formation was again a major problem.

Although few concrete, quantitative data were obtained, a number of problem areas were identified. The most severe problem was artifact formation, probably due to reaction of glass fiber filters with SO_x and/or NO_x and/or H_2SO_4 mist. Since the filters were not conditioned in such an environment this problem was heightened. Better substrate conditioning and use of less reactive filters should mitigate this problem. The problem of filter sticking is due to the approximately 15 percent moisture laden stack gases and relatively low temperatures. Better sampling procedures should correct this problem. No problem with plugging of critical orifices was observed. Screen plugging, however, did occur from prolonged use without cleaning or replacement. The assembly procedure and recommended cleaning schedule are discussed in Appendix A.

More field work is necessary to further study diffusion classifier performance, with attention to substrate selection and conditioning, and better sampling procedures. No serious operating problems were encountered with the diffusion classifier and it performed as intended.

4. DATA REDUCTION PROCEDURE

The procedure which has been chosen is based on Twomey's nonlinear iterative formula. The basic computer program was obtained from Dr. E. O. Knutson and modified for our use.

The program has been written so that particle size histograms, geometric mean diameters and standard deviations are calculated and printed out for input mass percent penetrations based on input data which include flow rate, temperature and stack pressure. Number of class intervals, width of class interval, and starting value can be set as required.

There are three major sections in this procedure: calculation of penetration characteristics of various numbers of screens from the generalized penetration function, Twomey's nonlinear iterative formula, and calculation of geometric mean diameter, standard deviation and root mean square error, and plotting of histograms. Twomey's nonlinear iterative formula is incorporated in an algorithm which starts with an initial assumption for the size distribution and then refines it by a series of small changes to improve the fit to the observed penetrations. In this case the initial assumption has been that the distribution is uniform, with each size having a penetration equal to 1/n times the observed penetration in the stage with no screens, which is 100 percent, where n is the number of sizes being considered. The refined penetrations are then obtained by applying Twomey's nonlinear iterative formula until the calculated mass percent penetrations are close to the measured mass percent penetrations which are input to the program. Normally the number of iterations is restricted to thirty or less. This procedure is explained in greater detail in papers by Knutson and Sinclair (Reference 7), and Twomey (Reference 8).

The computer program has been used in some preliminary work with field data and has been tested with monodisperse aerosol data and polydisperse aerosol data. Agreement was only fair for the monodisperse aerosol data and it appears that the program can not handle data with small standard deviations. In another test, the penetration function for screens, equation (3), was used to calculate penetrations of a polydisperse aerosol (MMD = 0.1 μm and σ_g = 2) through 5, 10, 20, and 36 screens. These penetrations were then input to the program and the resulting outlet distribution characteristics were: MMD = 0.124 μm and σ_g = 2.

The program worked quite well with one set of field data and one set of polydisperse aerosol data. However, more work needs to be done with the program, including error analysis and further testing with known distributions. The capabilities of the program should be enhanced to include log - probability plot presentation. Finally, a study of the program is needed to improve the accuracy of the results.

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